Developing a Gaertner Ellipsometer for Thin Film Thickness Measurement

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Abstract

It is after years of usage or due to an accident that a He-Ne (632.8nm) Gaertner Ellipsometer is sometimes found dysfunctional. Causes can be that its energizing laser power supply has gone bad or the laser does not release a beam. Unless one loans a good power supply to test the laser tube, it is unlikely to find why it is not releasing a beam. The last alternative is to dispose of both and buy a new He-Ne laser with its power supply, which is what we resorted to. Even after a tedious search it was only available with a smaller tube diameter and had to be retrofitted with a suitable collar around it to center it exactly like the previous one. Thus, we present how such an ellipsometer was developed to measure thickness of thin films. While a number of materials and structures can be identified our focus is mainly on the oxides and photoresists. The method can be used to evaluate multi-layers, nanostructures and complex mediums. In this paper development of such an ellipsometer is discussed. This ellipsometer is a fixed angle single wavelength ellipsometer and it provides a non-destructive optical technique for measuring the oxide thickness, or photoresist thickness, as well as the optical index of refraction at the measuring wavelength. As usual, the ellipsometer becomes specifically accurate below 10nm thickness films, and makes use of change of state of the polarization in the incident light after being reflected from the incident surface. The state of polarization of light is evaluated by determining the relative amplitude of the parallel and perpendicular components, and by the difference of phase between these two components.

Keywords: Enhancing the process of Engineering Education, Problem based Education, Student Research Experience

Introduction

Knowledge of ellipsometry to measure optical and physical properties of thin films and electronic materials promotes application-oriented studies in materials science and engineering. It enhances engineering education as one discovers better ways of doing such evaluations. Ellipsometer generally uses polarized light to non-invasively study a multi-layer or a single layer thin film material on a substrate. It can also study the bulk of the substrate. Mainly single wavelength ellipsometers are used for simple systems such as a single layer non-absorbing film, but they are constrained to give only two parameters. There are two other variations of the technique, which give more details. The technique of ellipsometry is most applicable to thickness of thin films on a silicon wafer or some standard highly absorbing substrate. The surface of the wafer carrying the dielectric film (silicon dioxide) is illuminated...
by a polarized single wavelength beam, which is shot at an angle to the surface. Both the oxide and the silicon surfaces reflect the beam (see Fig.1). Once the difference in the polarization is measured, the thickness of the oxide can be measured. When a beam is reflected from a single surface, it will shoot further polarized light directly into the detector according to the angle of incidence. At that point, readings can be observed and measurements can be taken. Yet, in some instances there are multiple surface wafers where various reflected beams will determine the optical path difference between the two surfaces.

**Ellipsometry**

In single surface wafers, the beam, which is reflected into the detector from the surface of the wafer, loses amplitude due to a portion of the beam penetrating the surface and the remaining portion\(^3,4\) being reflected into the detector.

The angles at which the beam is measured are usually delta (\(\Delta\)) and psi (\(\Psi\)). Delta (\(\Delta\)) measures the difference in phase change which is an equation that looks like \(\Delta_p-\Delta_s\) and the \(\Psi\) measures the \(\tan^{-1}\left(\frac{R_p}{R_s}\right)\). In the equation, \(R_p\) represents the reflection coefficient of the \(p\) constituent (parallel to the incidence plane), and \(R_s\) represents the reflection coefficient of the \(s\) constituent. \(\Delta_{p,s}\) represents the phase shifts which are noticed during reflection. If there was just a difference in reflection coefficients, and no phase shifts occurred, the light would continue to be plane polarized after reflection, but the plane of polarization could still be rotated. This would result in usage of \(\left(\frac{R_p}{R_s}\right)\) or \(\Psi\) to measure the change in the analyzer angle.

In figure 2(a) it is important to note that the electric vector \(E\) lies perpendicular to the direction of travel but it is allowed to have any orientation in the plane of the plane-wave propagation. Most times there will be \(E\) vectors with multiple different directions of its...
components. In figure 2(b), polarized light is observed in conditions of s and p projections, which are in similar in phase but not always in amplitude.

VASE

Variable angle spectroscopic ellipsometry (VASE) is a widely used tool for measuring the thickness of thin films and measuring material/optical properties of single layer or multilayer structures. Figure 1 shows how a polarized light beam is reflected from a sample at a tilted angle of incidence, $\phi$. The light beam, which is linearly polarized, is reflected from the surface of the sample into the detector from which the quantity of the change in polarization is read. This reading of the change in polarization is utilized for the physical properties of the sample used.

The basis for the theory of ellipsometry is Fresnel reflection equations or transmission equations for polarized light beams at each boundary or layers between different materials. The measurements are expressed in conditions of an amplitude ratio which is psi ($\Psi$), and phase quantity which is delta ($\Delta$).

$$\tan(\Psi)e^{i\Delta} = \rho_{\sim} = \frac{r_p}{r_s}$$

In this equation $r_p$ and $r_s$ stands for the complex Fresnel reflection coefficients for p- and s-polarized light. The angle of incidence and the wavelength is what is measured by VASE using the complex ratio, $\rho_{\sim}$, as a function.

In most of the materials the optical properties can be calculated directly from the ellipsometry measurement using an equation as such with the known angle, $\phi$:

$$\varepsilon = \varepsilon_1 + i\varepsilon_2 = n = \left|\frac{n^2 + ik}{n^2 - k}\right| = \sin(\phi)\times \left[1 + \tan(\phi)\frac{(1-\rho)/(1+\rho)}{2}\right]$$
Since the spectral range and number of wavelengths measured depend on the technical application, commercial ellipsometers are available with VUV to the far infrared (IR) span. We restricted to near infrared. Moreover, multiple wavelengths and multiple angles of incidence are used to test the measurements and model thick and unknown film structures to see which wavelengths and angles would be best.

**The Faraday Modulated Nulling Ellipsometer**

Figure 3 shows a ray diagram of the Faraday-modulated\(^5\) self-nulling ellipsometer. The linearly polarized beam (L) and the quarter wave plate (Q), gives an elliptically polarized light, which is made circular due to the effect of wave plate. There is a Nicol-prism (P), which polarizes the light and makes it linear where the intensity is not dependent of the polarizing angle, P. In this case, the ellipticity of this beam is dependent on the polarizer angle, P, in order to give out a beam, which is linearly polarized to reflect off the surface of the wafer. Now, after the light beam has gone through the quarter wave plate, it goes through the nulling device, F. This device nulls the beam by slightly rotating the polarization of the beam after it has passed through the polarizer and before it reaches the analyzing device. Once reflected, Nicol-prism (A) analyzes the beam, when it is adjusted to the correct or appropriate analyzing angle, gives off a null light beam to the laser detector, (D).

In the diagram, the linearly polarized light beam is reflected from the surface of a wafer, which makes the reflected light elliptically polarized. On the other hand, when the light is elliptically polarized correctly and reflects from the surface of the wafer, then the reflected light is linearly polarized. This is what an ellipsometer does, measures the change in the reflected light’s polarization. This polarization is induced by Faraday modulation in an optical medium ‘F’ due to a corresponding electric field. The plot between the measured P and A values gives you the refractive index and absorption coefficient of the film using computer fitting of these values for various thickness trajectories (plot)\(^5\).

**Semiconductor Measurements and Instruments**

Since it was necessary to align our instrument, below-mentioned procedure was followed:
Setting of the instrument:

1. Without using the wave plate in the ellipsometer, set the analyzer and the polarizer arms to 90° and align the laser with optics to achieve maximum transmission in the detector.
2. Adjust the polarizer and the analyzer arms to an incidence angle of ~57° or Brewster angle of incidence of a standard reflector, e.g., micro-slide glass.
3. Adjust or remove the analyzer, or set it so that its plane of transmission is approximately parallel to the plane of incidence. Rotate the polarizer for a minimum transmission. This becomes P= 0° for the polarizer. Adjust the scale accordingly.
4. Relocate the polarizer to 90° incidence and adjust the analyzer for minimum transmission. Set analyzer scale at 90°, i.e., A=90°
5. Set the polarizer and analyzer arms to the desired angle of incidence, e.g., 70°, level the stage, by raising or lowering until light is centered.
6. Insert a silicon wafer that is chemically clean and centered on the sample holder.
7. Set the polarizer angle at zero and adjust the analyzer angle for minimum. If the outcome is not yet at 90°, adjust the analyzer angle slightly until it reaches 90°
8. Place the quarter wave plate in the beam, with P=0°, A=90°, adjust the compensator for extinction. Set its index to zero. Now your instrument is set for measurements.

One can calculate the reflection coefficients by using a particular equation in which we use the phase shift that the light beam experiences in traversing the film or films. This also combines them resulting in an overall reflection coefficient and phase shift (Ψ and Δ). Using a program called ELLIPSO [6], the measured values of Ψ and Δ was fitted to obtain the thickness values. Once those were obtained, the equations could be solved by substituting the acquired numbers into the following equation. From that, the measurement of the thickness of the film on the wafer was obtained.

\[ δ = 2\pi t \left( n^2 - \sin^2 φ \right)^{1/2} / λ \]

Once the numbers where obtained from the equation and the thickness of any standard film on a wafer was found, the numbers from other measurements were applied to the ELLIPSO program to get further readings dealing with the thickness. As shown in Table 1 the resulting numbers for the delta, psi, the thickness in nanometers, measurements for the film (NF, KF), and the measurements for the silicon wafers (NS, KS) are given for silicon dioxide films on Silicon substrates. In an identical manner one can determine the thickness of a photo-resist film on silicon if the approximate first order value of its thickness and its NF and KF, i.e., the refractive index and the absorption coefficients are known. The accuracy of the instrument will be verified if we can measure various films of standard refractive index and thickness.

**Conclusion**

The method described above can give accurate measurements of thin film thickness and refractive index of thin optical films like gate oxides and photo-resists. Measurements for S1818 a positive photoresist by Shipley Corp. is underway to test the method for organic thin films. It is felt that ellipsometric measurements of inorganic and organic materials is a good subject to enhance experience in engineering education of undergraduate seniors and
beginning graduate students. This project was a re-engineering exercise for the involved students.

Table 1.

<table>
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<tr>
<th>IE</th>
<th>DEL (°)</th>
<th>PSI (°)</th>
<th>Thickness (nm)</th>
<th>NF</th>
<th>KF</th>
<th>NS</th>
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References

Shatter Roy is a junior majoring in electrical engineering at Southern University. He is a present member of IEEE (Institute of Electrical and Electronics Engineers). For the past two semesters, Shatter has done research on ellipsometric studies under the supervision of Dr. Pradeep K. Bhattacharya, mentor and professor at Southern University. This semester, he is doing research on the measurement of thickness of organic films such as photo-resists and polyimides.

Aubry Turner is a junior majoring in electrical engineering at Southern University in Baton Rouge, LA. He is a SMART (Strengthening Minority Access to Research and Training) scholar and a present member of IEEE (Institute of Electrical and Electronics Engineers). Aubry has done research on the study of thin film thickness errors of silicon dioxide films, along with Dr. Bhattacharya, professor and mentor at Southern University.

Pradeep Bhattacharya is a Professor in Electrical Engineering at Southern University, Baton Rouge. Earlier he was an Associate Professor at Louisiana State University from July 1990 to June 1993. He was a Summer Professor Intern at Advanced Micro Devices from June 93 to August 93. He has worked at Microelectronics Center of North Carolina, RTP for four years. His field of specialization is electronic materials, processing and process modeling. Reliability and device characterization before and after interaction with electrons, ions and X-rays also match his interests. His present interests lie in, Fuel Cells, X-ray lithography, MEMS and studies of nanostructures in semi-conducting structures.